PRECISE T & F INTERCOMPARISON VIA VLF PHASE MEASUREMENTS

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ABSTRACT

The Indian subcontinent does not fall in the groundwave range of any LORAN-C transmission. As such, at present the only alternative technique in this region for convenient and routine T & F intercomparison is via VLF phase measurements. At NPL, New Delhi, continuous phase recording of the 16 kHz transmissions from GBR (UK) is being made. In addition the published midday phase data of GBR from several laboratories-NPL (UK), RGO(UK), PTB (FRG) and USNO (USA) - are being received regularly. In the present paper we discuss T & F intercomparisons between the local time scale, UTC (India), at NPL and those at the above mentioned laboratories, using the VLF phase data. A major factor which limits the accuracy of long term comparison is the seasonal variation in the VLF propagation delay over long paths. It is shown that by taking into account the seasonal propagation delay variations in a semiempirical way the accuracy of T & F comparisons can be considerably improved. In fact over a one year period accuracy of few parts in 10^{14} in frequency and 1-2 μ sec in time have been obtained.

The relative frequency offset difference between UTC (India) and UTC (PTB) evaluated in the present work as $(7.0 \pm 0.1) \times 10^{-13}$ agrees very well with that obtained via the satellite experiment described in a companion paper.

INTRODUCTION

The National Physical Laboratory (NPL), New Delhi, India has the statutory obligation of maintaining the India

Standards of time and Frequency. This is being achieved at present with the help of two commercial cesium clocks: NPL-1 (Oscilloquartz Model 3200) and NPL-2(Hewlett Packard Model 5061A with option 004). A time scale, UTC (India), is being maintained using the NPL-1. One of major problems being faced by us at NPL is that of a regular time and frequency transfer link between UTC (India) with those of the other international timekeeping laboratories. The Indian subcontinent does not fall in the groundwave range of any LORAN-C transmitter thus prohibiting the use of this technique.

The first serious attempt in having an accurate link was made in May-June, 1979, when a two way satellite time transfer experiment was performed between NPL and PTB, West Germany (Mathur et al, 1980 and references there in). With the help of this experiment UTC (India) was synchronised with UTC (PTB). From July, 1979 onwards we are continuously tracking the phase of 16 kHz transmissions from GBR (UK). The choice of this station was dictated by the fact that; (a) the received signal strength at our location is very good so that a precise phase tracking is possible and (b) there are several timekeeping laboratories which track this station and publish their data. We are regularly receiving the GBR phase data from PTB (FRG), USNO (USA), NPL (UK) and RGO (UK). Utilizing the VLF data it has been possible to establish a fairly precise link between UTC (India) and UTC of the abovementioned laboratories as will be described in the subsequent sections.

A confirmation of the accuracy of the VLF links was made possible with a portable clock trip from USNO in September, 1980. This is described briefly in a separate subsection.

THE TECHNIQUE

The VLF time transfer technique has been described by Becker et al (1969). This basically consists of recording the time difference between the 1 pps of the local time scale and some specified phase (generally the positive zero crossing) of the received VLF signal appearing just subsequently. This measurement is referred to as the 'phase time', or simply 'phase' of the received signal relative to the local time scale. The recording is done at the local noon over the path mid point when VLF propagation conditions are most stable. Subtracting the daily values of phase measurements recorded at two laboratories gives the difference between their time scales. This difference is ambiguous to an additive constant which involves the difference between the propagation delays over the two paths. While this ambiguity is immaterial for frequency comparison between the two time scales it has to be eliminated if a time comparison is desired. Elimination of the additive constant can be achieved by an initial calibration with the help of either a portable clock or two way satellite experiment.

A major factor which degrades precision and accuracy of the VLF time transfer is the non constancy of the propagation delay. There is a day to day jitter in the propagation delay because of the normal variability of the ionospheric D-region. This is more pronounced during winter than during summer, as will be shown inthe next section (see also Belrose, 1968). The jitter evidently reduces the precision of the link. Sudden ionospheric disturbances (SID) due to solar flares may occasionally cause path anomalies, but these generally last for short durations and can be isolated by careful inspection of the data (Reder, 1971).

In addition, over long paths there are also systematic seasonal variations in the propagation delay which can some times be as large as 15 μ sec (Iijima et al, 1968; Swanson & Kugel, 1972). If these are not taken into account then they may introduce significant inaccuracy in the time and frequency comparisons. The seasonal variation in the propagation delay occurs mainly due to variations in the D-region ionization. This consists of two parts, namely (a) seasonal variation of the Solar Zenith angle at the mid path noon and (b) variations in the mesospheric neutral atmospheric constituents, which are to some extent related to meteorological phenomena (Belrose 1968). Of the above, only the first part, (a), can be modeled with definiteness. It has been shown by Swanson & Kugel (1972) to be of the form $M(\overline{1-\cos\chi})$, where, $\overline{\cos\chi}$ is the average of the cosine of the solar zenith angle χ over the path at the midday. M is an empirical constant dependent on the propagation path and to some extent on the solar activity.

THE DATA

(a) NPL (India) data : The midday phase observations of the 16 kHz GBR signal relative to UTC(India) recorded daily between 08-30 to 09-30 UT are shown in Fig.1(a) for the period 10th July, 1979 to 10th July, 1980. Twice during the one year time the NPL-1 underwent discontinuities in operation for short periods. Once during 23-25 August, 1979 and again during 30 August - 7 September, 1980. In both cases it was possible to restart UTC (India) by synchronizing NPL-1 with NPL-2 and giving suitable time corrections (of 1.3 and 5.5 μsec respectively). The time corrections were determined from the intercomparison data between these two clocks which was taken periodically throughout.

We observe the following features in Fig.1(a). The day to day variability is much smaller in summer than in winter. The rms jitter in summer is less than 1 μsec while in winter it is about 2.5 μsec. There is a gradual drift in the phase data arising due to a relative frequency offset between UTC (India) and the transmitted frequency of GBR. This drift is modulated by a seasonal variation in the propagation delay. As mentioned in the earlier section, the Solar Zenith angle related seasonal variation of the form $M(1-\overline{\cos\chi})$ can be modelled and eliminated. To determine $\overline{\cos\chi}$ we follow Iijima et al (1968). We divide the propagation path (6700km) into 10 equal segments and determine $\cos\chi$ at the midpoint of each. The average of these values gives $\overline{\cos\chi}$ over the path. To determine the value of M we take help of the observed diurnal variation of phase delay. It has been shown by Swanson and Kugel (1972) that around midpath noon, the temporal variation of phase delay is also of the form $M(1-\overline{\cos\chi})$. We thus make comparisons between the temporal variation of the observed phase delay and that of the calculated factor $M(1-\overline{\cos\chi})$ by varying M. The value of M which gives best agreement between the forms of the two variations is selected. Utilising the whole years data the best value of $M=12.5\pm1$ was obtained. In Figs.2 and 3 we have shown as illustrations the observed diurnal phase for groups of 15 days in April and June and the calculated $M(1-\overline{\cos\chi})$. The good agreement between the two is evident. Adopting the above value of M the calculated seasonal variation of $M(1-\overline{\cos\chi})$ at the midpath noon for the full year is shown in Fig.1(b). This shows an annual variation with a summer to winter phase retardation of 7 μsec. On subtracting out this seasonal variation from the observed data in Fig.1(a) we get the resultant variations as shown in Fig.4(a). The phase drift now appears more regular but there still persist some short period variations during the period September, 1979 to February, 1980 with peak amplitudes of 2-3 μsec.

(b) PTB data: The midday phase observations of GBR relative to UTC(PTB) is shown in Fig.4(b). This path is only 790 km long and the solar zenith angle related seasonal variation in the phase delay is not expected to be significant. It is not apparent in the data also. During the period from September'79 to February'80, the nature of variations in the PTB data are very much similar to NPL (India) data in Fig.4 (a). It is notable in this connection that GBR-PTB path is almost overlapping with 1/8 of the GBR-NPL (India) path. This indicates the possibility that the shorter period variations mentioned above are arising from this portion of the path.

(c) RGO data: The midday phase variation of GBR relative to UTC (RGO) in shown in Fig.4(c). In this case also the path length being very short (180km) seasonal variations are almost absent.

(d) USNO data : The midday phase variations of GBR relative to UTC (USNO) are shown in Fig.5(a). The propagation path in this case is long (5800 km) and so the solar zenith angle related seasonal variation is significant. As we do not have the diurnal phase variation for this station it is not possible to determine M as was done earlier for NPL data. In absence of anything better we have just adopted the same value of M=12.5 and calculated the variation of midday values of $M(1-\overline{\cos\chi})$. This is shown in Fig 5(b). Subtracting variations in Fig 5(b) from those in Fig 5(a) we get the resultant as shown in Fig 5(c). In this case also during September 1979 to February 1980, we observe anomalous variations of similar nature as in PTB and NPL (India) data. But these variations are of larger magnitude (~12 μsec peak to peak)

(e) NPL (UK) data : The midday phase observation of GBR relative to UTC (NPL,UK) showed occasional jumps of 5,10 and 15 μsec over the whole year. These were most probably due to some equipment malfunction. Thus the data from this station have not been used.

RESULTS AND DISCUSSION

For intercomparison between UTC (India) and UTC of the other laboratories, the individual phase data in Figs 4(b), 4(c) and 5(c) have to be subtracted from Fig 4(a). In Fig 6 we have shown : (a) UTC (India)-UTC (PTB), (b) UTC (India)- UTC(RGO) and (c) UTC (India)-UTC(USNO). It is clear that of the three links the one with PTB has the minimum jitter and anomalies due to propagation variations. In Fig.6 we have drawn regression lines through the points which represent the overall drift rates. The slope of these straight lines give the relative frequency offset, S, between UTC (India) and the other UTC scales. Following results are obtained.

$$S_{India,PTB} = (7.0 \pm 0.1) \times 10^{-13}$$

$$S_{India,RGO} = (7.3 \pm 0.2) \times 10^{-13}$$

$$S_{India,USNO} = (6.9 \pm 0.2) \times 10^{-13}$$

The value of $S_{India,PTB}$ obtained above is in fairly good agreement with a value of $(7.1 \pm 0.5) \times 10^{-13}$ obtained via the satellite experiment (Mathur et al, 1980) during May-June, 1979. This indicates that the UTC (India) has been maintaining a fairly constant rate. The relative offset with the other two laboratories are also consistent (within the uncertainities) with LORAN-C links connecting these. LORAN-C link results have been calculated as follows :

$$S_{PTB,USNO} = 0.4 \times 10^{-13}$$

$$S_{PTB,RGO} = 0.0 \times 10^{-13}$$

To get an idea of the precision of the frequency transfer estimates we have made some computations of the variance, σ_y, on the India-PTB link which is the best of the three links. We get the following values :

$$\sigma_y \ (\tau = 1 \text{ day}) = 2 \times 10^{-11}$$

$$\sigma_y \ (\tau = 10 \text{ days}) = 3 \times 10^{-12}$$

$$\sigma_y \ (\tau = 30 \text{ days}) = 2 \times 10^{-13}$$

$$\sigma_y \ (\tau = 100 \text{ days}) = 1 \times 10^{-13}$$

The σ_y estimate on the other two links are some what higher than the above.

The graphs in Fig.6 have not been given in absolute terms i.e., the origins of the graphs are not shown. Absolute calibrations is necessary for actual time transfer between UTC (India) and other UTC scales. As mentioned earlier this was performed by the satellite experiment in May-June, 1979. As a result of this experiment it was found that on 29 June'79 UTC (India)-UTC(PTB) = (2.7 ± 0.1) μsec. The VLF observations were started on 10 July onwards (as the GBR transmission was off for a month before this). Thus in Fig 6(a) we assign a value of 2.7 μsec to the ordinate where the regression line crosses the abscissa on 29 June' 79. Since the difference between UTC (PTB) and UTC (RGO) and UTC(USNO) are known from the LORAN-C links it is possible to calibrate the other two graphs also.

PORTABLE CLOCK TRIP

A portable clock trip from the USNO was made during 18-21, September,1980. This made it possible to evaluate the accuracy of the time transfer accuracy of the VLF link. In Fig. 7 we have shown the results of only one link UTC(India)-UTC(PTB) extended upto the end of September'80. There are two crosses in Fig. 7 on 29 June '79 representing the satellite experiment time transfer and on 20 September '80 representing the portable clock result. The discrepancy between results of the portable clock and the regression line predicted by the VLF data is only 1.5 μsec which is quite small.

CONCLUSION

In this paper we have discussed a VLF time and frequency intercomparison link between UTC (India) and UTC of PTB, RGO and USNO. It is clear that the India-PTB link is the best of the three. It has been shown that by taking due account of the seasonal variations over long paths it is possible to achieve frequency intercomparison to a few parts in 10^{14} over one year period. Time transfer can be achieved to an accuracy of 1-2 μsec.

We realise, however, that this accuracy level is still not acceptable to BIH for inclusion of UTC (India) in the international UTC coordinated by them. In fact a similar problem must be faced by many other remote timekeeping laboratories which are not covered by LORAN-C groundwaves or regular portable clock trips.

Our future plans in improving our links with the international time keeping community are : (a) reception of more VLF stations possibly OMEGA(JAPAN,Liberia, La Reunion), (b) having regular portable clock trips,(c) using the NNSS satellite signals and (d) using some geostationary satellite links on a regular basis.

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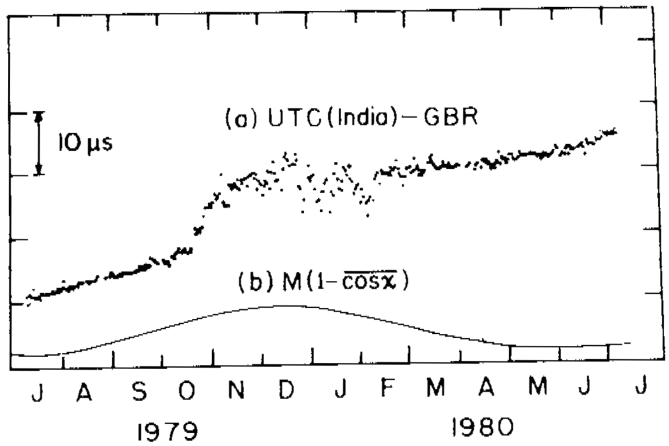

Fig.1 (a) Daily values of GBR phase relative to UTC(India).

(b) Calculated seasonal variation factor M(1-$\overline{\cos\chi}$) for GBR-NPL path.

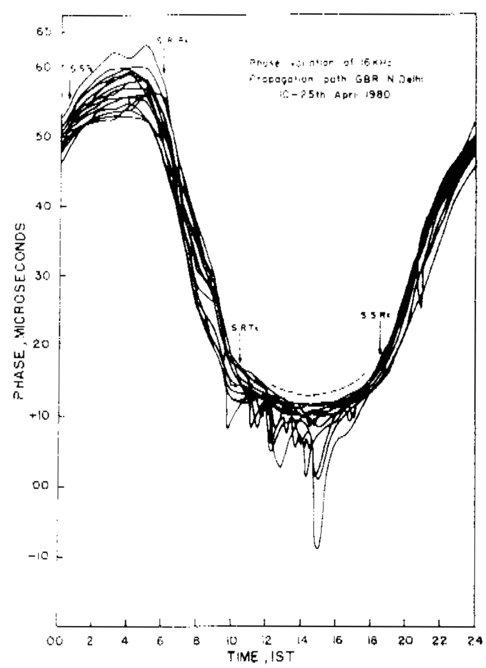

Fig. 2 Diurnal variation of GBR phase for 15 days in April'80 compared with the variation of M(1-$\overline{\cos\chi}$) (dotted line) around midday.

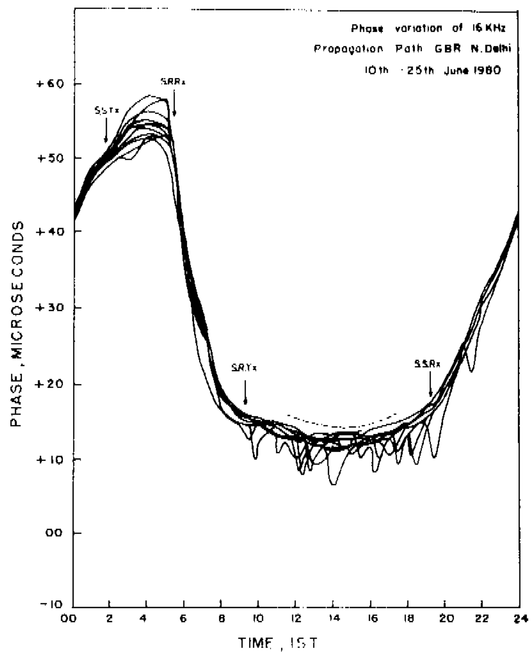

Fig. 3 Same as in Fig.2 for 15 days in June'80.

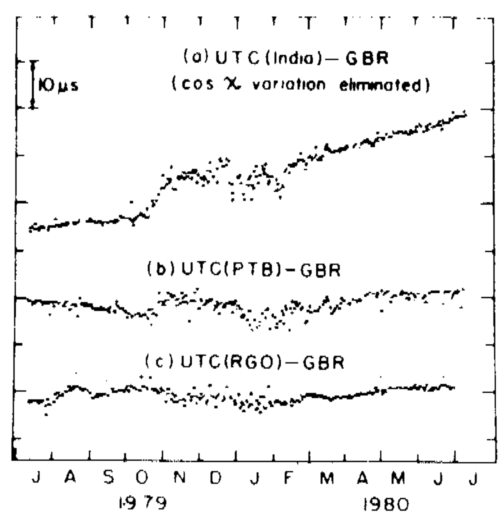

Fig.4 (a) GBR phase relative to UTC(India) corrected for solar zenith angle variations. (b) GBR phase relative to UTC(PTB). (c) GBR phase relative to UTC (RGO).

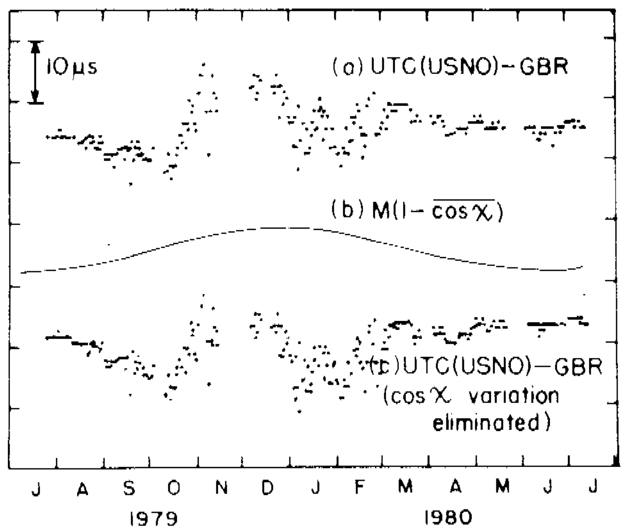

Fig.5 (a) GBR phase relative to UTC(USNO). (b) Calculated seasonal variation factor $M(1-\overline{\cos\chi})$ for GBR-USNO path. (c) GBR phase relative to UTC(USNO) corrected for solar zenith angle variations.

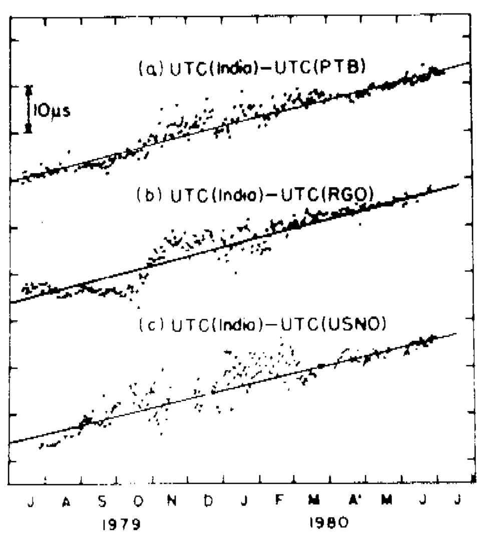

Fig. 6 (a) UTC (India) - UTC (PTB). (b) UTC (India)- UTC (RGO). (c) UTC (India) - UTC (USNO).

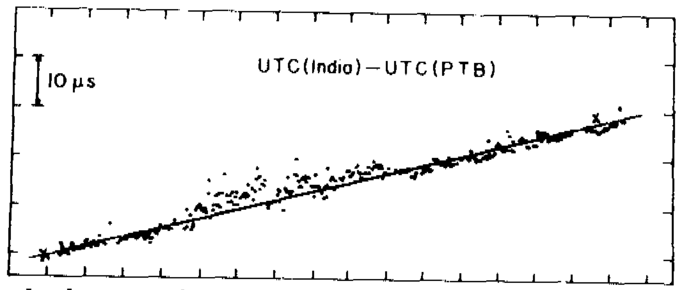

Fig.7 UTC (India)- UTC (PTB). The two crosses shown on 29 June'79 represents the satellite time transfer and on 20 Sept'80 represents the portable clock check.